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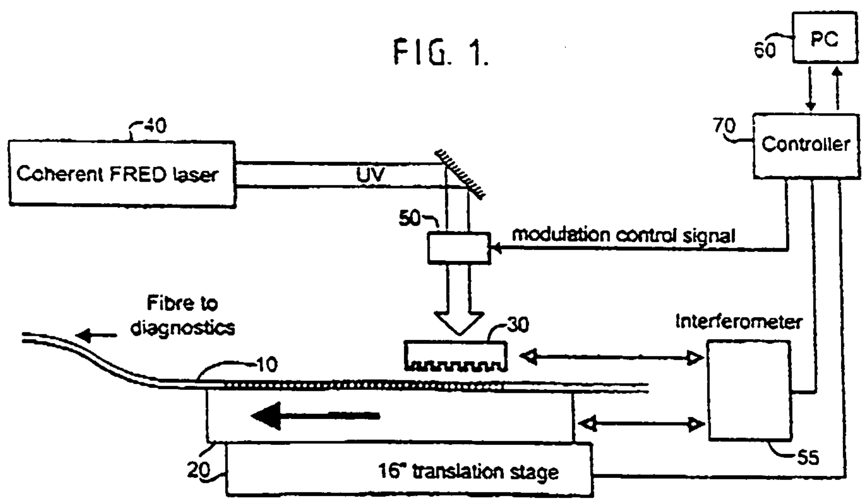
(54) Fabricating optical waveguide gratings

(57) An optical waveguide grating having a plurality of grating lines of refractive index variation is made by:
(i) repeatedly exposing a spatially periodic writing light pattern onto a photosensitive optical waveguide 10; and
(ii) moving the writing light pattern and/or the waveguide between successive exposures of the writing light pattern, so that each of at least a majority of the grating lines is generated by at least two exposures to different respective regions of the writing light pattern Acousto-optic modulator 50, phase mask 30 and crossed roller bearing translation stage 20 are shown.

FIG. 1.



At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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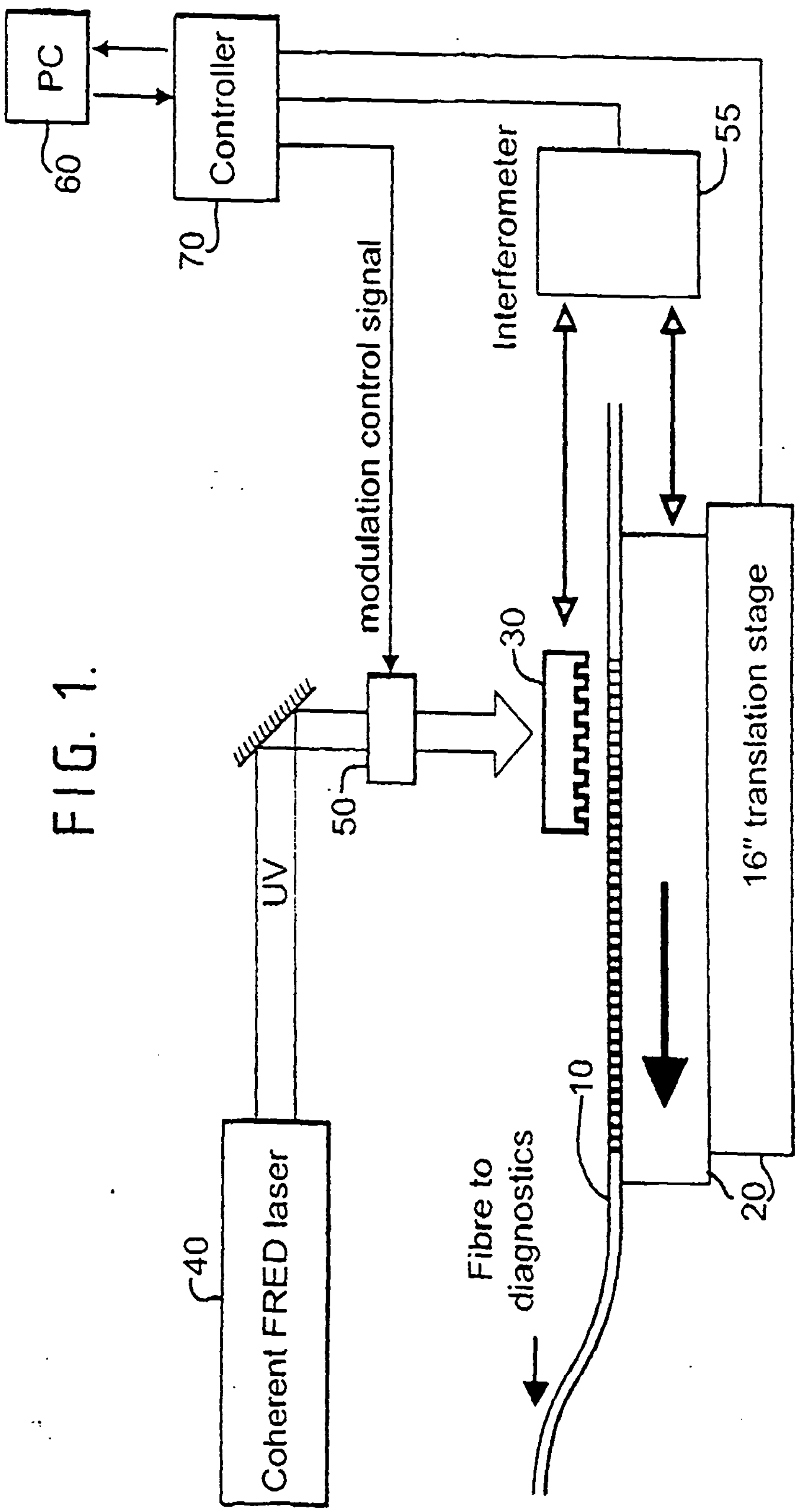

PC
60
Controller
70
modulation control signal
Interferometer
55
UV
50
30
16" translation stage
10
20
Coherent FRED laser
40
Fibre to
diagnostics

FIG. 1.

FIG. 2a

FIG. 2b.

FIG. 2c.

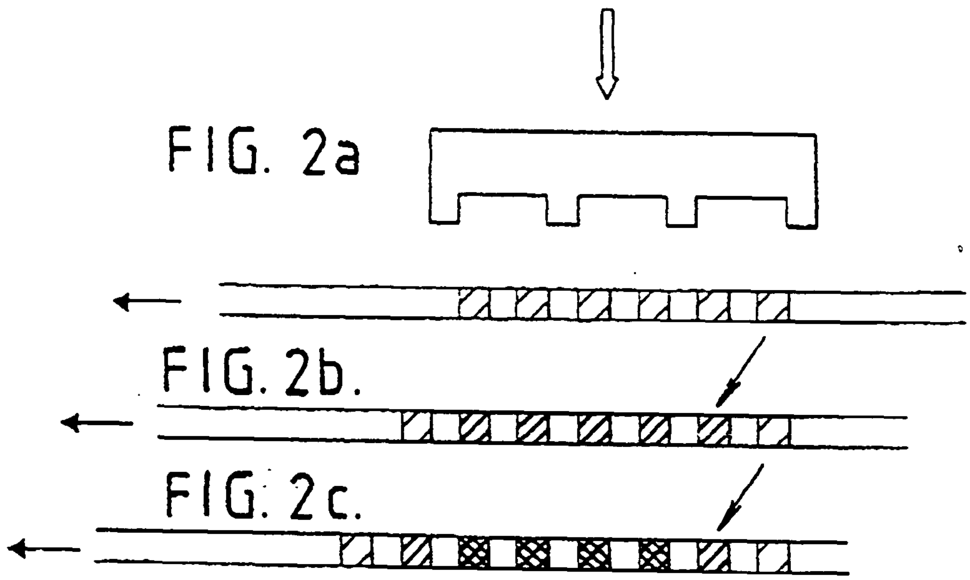


FIG. 3a.

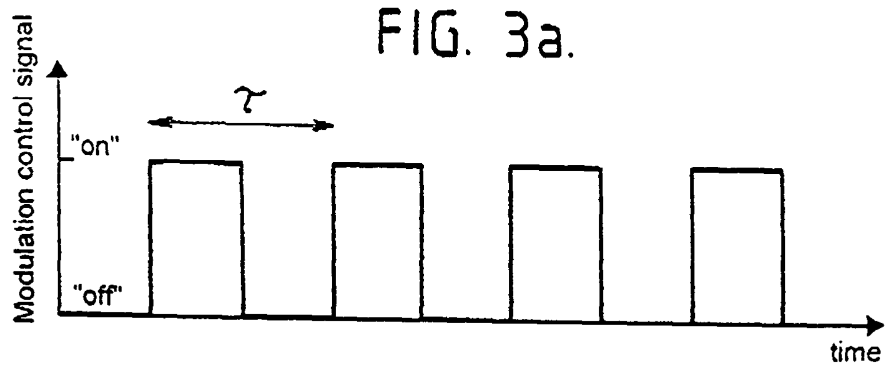


FIG. 3b.

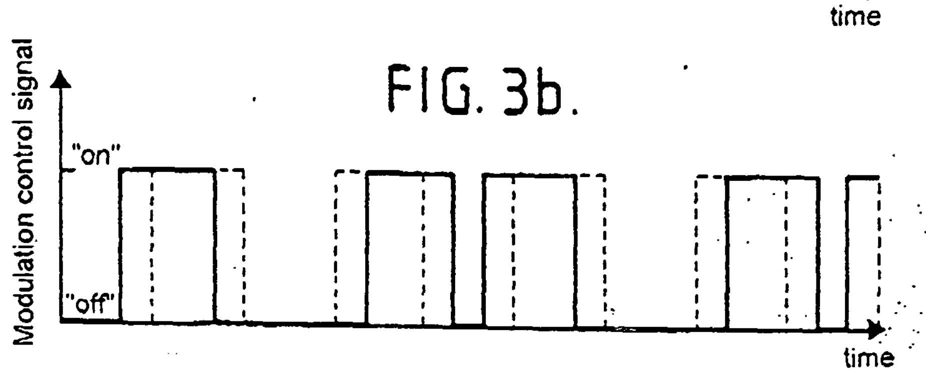


FIG. 4a.

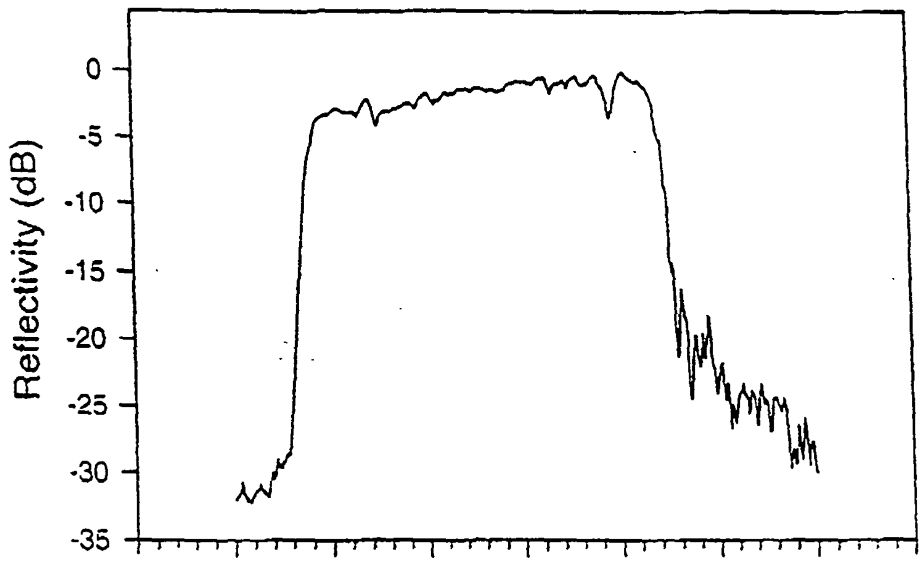
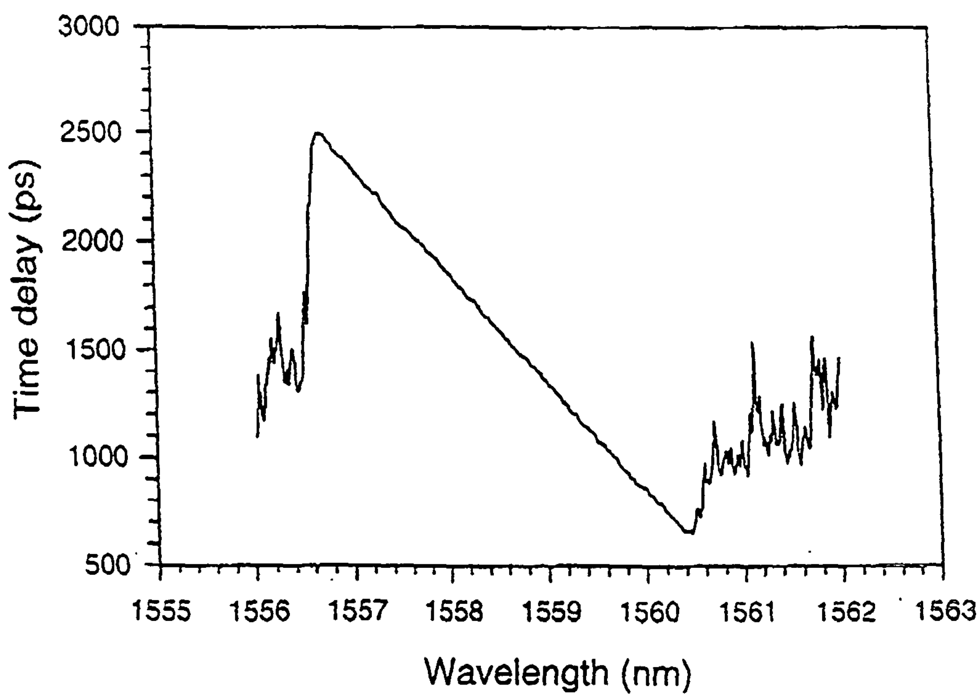

0
-5
-10
-15
-20
-25
-30
-35
Reflectivity (dB)

FIG. 4b.


3000
2500
2000
1500
1000
500
Time delay (ps)
1555
1556
1557
1558
1559
1560
1561
1562
1563
Wavelength (nm)

2316760

FABRICATING OPTICAL WAVEGUIDE GRATINGS

This invention relates to fabricating optical waveguide gratings.

Dispersion compensation is an attractive technique allowing the upgrade of the existing installed standard fibre network to operation at 1.5μm where it exhibits a dispersion of ~ (about) 17ps/nm.km which would otherwise prohibit high capacity (eg. 10Gbit/s) data transmission.

Chirped fibre gratings are currently the most attractive technique for fibre dispersion compensation [1]. This is because they are generally low loss, compact, polarisation insensitive devices which do not tend to suffer from optical non-linearity which is the case with the main competing technology, dispersion compensating fibre.

For present practical applications chirped gratings must exhibit both high dispersion, ~1700ps/nm, sufficient to compensate the dispersion of around 100km of standard fibre at a wavelength of 1.55μm, and a bandwidth of around 5nm. This implies a need for a chirped grating of length 1m.

Fibre gratings are generally created by exposing the core of an optical fibre to a periodic UV intensity pattern [2]. This is typically established using either an interferometer or a phase mask [3]. To date, phase masks are the preferred approach owing to the stability of the interference pattern that they produce. The length of the grating can be increased by placing the fibre behind the phase mask and scanning the UV beam along it. Techniques for post chirping a linear grating after fabrication include applying either a strain [1] or temperature gradient [4] to it. However these techniques are limited due to the length of the initial grating (~10cm with available phase masks) and the length over which a linear temperature or strain gradient can be applied. Alternatively more complex step chirped phase masks can be employed [5]. However, all of these techniques are currently limited to a grating length of about 10cm.

In addition to chirping the grating, it is also sometimes desirable to be able to apodise (window) the gratings to reduce multiple reflections within them and to improve the linearity of the time delay characteristics. A powerful technique has been developed which allows chirped and apodised gratings to be written directly in a fibre, referred to as "the moving fibre/phase mask scanning beam technique" [6].

This technique is based on inducing phase shifts between the phase mask and the fibre as the phase mask and fibre are scanned with the UV beam. Apodisation is achieved by dithering the relative phase between the two at the edges of the grating. Like all the previous techniques the one draw back with this technique is that it is again limited to gratings the length of available phase masks, ~10cm at present.

This problem has been overcome in one approach by Kashyap et al using several 10cm step-chirped phase masks [5]. These are scanned in series to obtain a longer grating. The phase "glitch" or discontinuity between the sections is subsequently UV "trimmed" to minimise its impact. However this is a time consuming and costly process. In addition the effect of the UV trimming will vary with grating ageing.

A technique for potentially writing longer gratings has been reported by Stubbe et al [7]. In this case a fibre is mounted on an air-bearing stage and continuously moved behind a stationary grating writing interferometer. The position of the fibre is continuously monitored with a linear interferometer. The UV laser is pulsed to write groups of grating lines with period defined by the writing interferometer. A long grating can be written by writing several groups of grating lines in a linearly adjacent series, with controlled phase between the sections. The phase shift between each group of grating lines is controlled via the linear interferometer and a computer which sets the time the laser pulses. A short pulse, ~10ns, is required such that the position of the writing lines is effectively stationary and accurately controlled with respect to fibre motion. Having said this, however, jitter in the pulse timing and in the linear interferometer position will give detrimental random phase errors in the grating. Chirped gratings can potentially be fabricated by continuously introducing phase shifts between adjacent groups along the grating. Obviously the maximum translation speed is limited by the number of grating lines written with one laser pulse and the maximum repetition rate of the pulsed laser. It is also proposed in this paper that apodisation is achieved by multiple writing scans of the grating.

This invention provides a method of fabricating an optical waveguide (e.g. an optical fibre) grating having a plurality of grating lines of refractive index variation, the method comprising the steps of:

(i) repeatedly exposing a spatially periodic writing light pattern onto a photosensitive optical waveguide; and

(ii) moving the writing light pattern and/or the waveguide between successive exposures of the writing light pattern, so that each of at least a majority of the grating lines is generated by at least two exposures to different respective regions of the writing light pattern.

Embodiments of the invention provide a number of advantages over previous techniques:

1. The realisation that the laser does not have to be pulsed but just has to be on for a particular duty cycle - preferably less than 50% of the period. This allows an externally modulated CW (continuous wave) laser to be used.

2. With this technique the grating lines are re-written by several successive exposures of the writing light beam at every grating period (or integral number of grating periods). Thus the footprint defined by the writing light beam is significantly overlapped with the previous lines. Significant averaging of the writing process is achieved thus improving the effective accuracy and resolution of the system, compared to that of [7] where a group of lines is written in a single exposure, and the fibre is then advanced to a fresh portion where a further group of lines is written in a single exposure.

3. Effectively controlling the grating writing process on a line-by-line basis allows accurate apodisation to be achieved. This may be performed in embodiments of the invention by dithering the grating writing interferometer position in the fibre to wash out or attenuate the grating strength whilst keeping the average index change constant.

4. The technique offers the further advantage that the CW laser may be extremely stable, whereas pulsed lasers (e.g. those used in [7]) may suffer from pulse-to-pulse instability which is not averaged. In addition the high peak powers of the pulsed laser may cause non-linear grating writing effects.

5. Arbitrary phase profiles and in particular a linear chirp can be built up by inducing phase shifts electronically along the grating as it grows. In a similar manner to the "Moving fibre/phase mask" technique [6] the maximum wavelength is inversely proportional to the beam diameter. This can be further improved in particular

embodiments of the invention by incorporating a short, linearly chirped phase mask. Thus as the fibre is scanned the UV beam may be also slowly scanned across the phase mask, an additional small phase shift is induced, whilst most significantly we have access to writing lines of a different period allowing larger chirps to be built up.

This invention also provides an optical waveguide grating fabricated by a method according to the above methods.

This invention also provides apparatus for fabricating an optical fibre grating having a plurality of grating lines of refractive index variation, the apparatus comprising:

a writing light beam source for repeatedly exposing a spatially periodic writing light pattern onto a photosensitive optical waveguide; and

means for moving the writing light pattern and/or the waveguide between successive exposures of the writing light pattern, so that each of at least a majority of the grating lines is generated by at least two exposures to different respective regions of the writing light pattern.

The various sub-features defined here are equally applicable to each aspect of the present invention.

The invention will now be described by way of example with reference to the accompanying drawings, throughout which like parts are referred to by like references, and in which:

Figure 1 is a schematic diagram of a fibre grating fabrication apparatus;

Figures 2a to 2c are schematic diagrams showing a grating fabrication process by repeated exposures;

Figures 3a and 3b are schematic timing diagrams showing the modulation of a UV beam; and

Figures 4a and 4b are schematic graphs characterising a 20cm grating produced by the apparatus of Figure 1.

Figure 1 is a schematic diagram of a fibre grating fabrication apparatus. An optical fibre (e.g. a single mode photorefractive fibre) 10 is mounted on a crossed roller bearing translation stage 20 (such as a Newport PMLW160001) which allows for a continuous scan over 40cm. The fibre 10 is positioned behind a short (~5mm) phase mask 30 (e.g a mask available from either QPS or Lasiris).

The fibre is continuously and steadily linearly translated or scanned in a substantially longitudinal fibre direction during the grating exposure process.

Ultraviolet (UV) light at a wavelength of 244nm from a Coherent FRED laser 40 is directed to the fibre/phase mask via an acoustic-optic modulator 50 (e.g. a Gooch & Housego, M110-4(BR)) operating on the first order.

The relative position of the fibre to the interference pattern of the phase mask is continuously monitored with a Zygo, ZMI1000 differential interferometer 55. The interferometer continuously outputs a 32-bit number (a position value) which gives the relative position with a ~1.24nm resolution. This output position value is compared by a controller 70 with switching position data output from a fast computer 60 (e.g. an HP Vectra series 4 5/166 with National Instruments AT-DIO-32F) in order that the controller can determine whether the UV beam should be on or off at that position. Whether the UV beam is in fact on or off at any time is dependent on the state of a modulation control signal generated by the controller 70 and used to control the acousto-optic modulator 50.

So, as each position value is output by the interferometer, the controller 70 compares that position value with the switching position data currently output by the computer 60. If, for illustration, the interferometer is arranged so that the position values numerically *increase* as the fibre scan proceeds, then the controller 70 detects when the position value becomes greater than or equal to the current switching position data received from the computer 60. When that condition is satisfied, the controller 70 toggles the state of the modulation control signal, i.e. from "off" to "on" or vice-versa. At the same time, the controller 70 sends a signal back to the computer 60 requesting the next switching position data corresponding to the next switching position.

If the fibre was scanned with the UV beam continuously directed onto the fibre, no grating would be written since the grating lines would be washed out by the movement.

However if the UV beam is strobed or modulated (under control of the switching position data generated by the computer 60) with a time period matching or close to:

[illegible]

[illegible]

This expression is based on a time period of temporally regular modulation of the UV beam, and so assumes that the fibre is translated at a constant velocity by the translation stage. However, more generally, the switching on and off of the UV beam is in fact related to the longitudinal position of the fibre, so that in order to generate a grating the UV beam should be turned on and off as the fibre is translated to align the interference pattern arising from successive exposures through the phase mask.

Figures 2a to 2c are schematic diagrams showing a grating formation process by repeated exposures of the fibre to the UV beam.

In Figure 2a, the UV beam from the acousto-optic modulator 50 passes through the phase mask 80 to impinge on the fibre 10. During the exposure process, the fibre 10 is being longitudinally translated by the translation stage 20 in a direction from right to left on the drawing. Figure 2a illustrates (very schematically) a refractive index change induced in the fibre by a first exposure through the phase mask.

Figures 2a to 2c illustrate a feature of the normal operation of a phase mask of this type, namely that the pitch of the lines or fringes of the interference pattern projected onto the fibre which give rise to the lines of the grating is half that of (i.e. twice as close as that of) the lines physically present (e.g. etched) in the phase mask. In this example, the phase mask has a "physical" pitch of 1µm, and the lines projected onto the fibre have a pitch of 0.5µm.

The UV beam is modulated by the acousto-optic modulator in a periodic fashion synchronised with the translation of the fibre. In this way, successive exposures, such as the two subsequent exposures shown in Figures 2b and 2c, generate periodic refractive index changes aligned with and overlapping the first exposure of Figure 2a. Thus, the refractive index change providing each individual grating "element" or fringe is actually generated or built up by the cumulative effects of multiple exposures through different parts of the phase mask as the fibre moves

along behind the phase mask. This means (a) that the optical power needed to generate the grating can be distributed between potentially a large number of exposures, so each exposure can be of a relatively low power (which in turn means that the output power of the laser 40 can be relatively low); and (b) the grating can be apodised by varying the relative positions of successive exposures (this will be described below with reference to Figure 3b).

Although each of the successive exposures of the fibre to UV light through the phase mask 30 could be a very short pulse (to "freeze" the motion of the fibre as the exposure is made), this has not proved necessary and in fact the present embodiment uses an exposure duty cycle in a range from below 10% to about 50%, although a wider range of duty cycles is possible. An example of a simple regular exposure duty cycle is shown schematically in Figure 3a, which in fact illustrates the state of the modulation control signal switching between an "on" state (in which light is passed by the acousto-optic modulator) and an "off" state (in which light is substantially blocked by the acousto-optic modulator). The period, τ, of the modulation corresponds to the time taken for the fibre 10 to be translated by one (or an integral number) spatial period of the interference pattern generated by the phase mask 30.

As the duty cycle for the UV exposure increases, the grating contrast decreases (because of motion of the fibre during the exposure) but the writing efficiency increases (because more optical energy is delivered to the fibre per exposure). Thus, selection of the duty cycle to be used is a balance between these two requirements.

Assuming linear growth, the index modulation, $n_g(z)$ in an ideal grating can be described as a raised cosine profile:

$$n_g(z) \propto 1 + \sin(2\pi z/\Lambda)$$

where z is the position down the fibre and Λ the grating period. With the new technique we obtain:

$$n_g(z) \propto (\Delta\Lambda_{ON}/\Lambda)[1 + \{\sin(\pi\Delta\Lambda_{ON}/\Lambda)/(\pi\Delta\Lambda_{ON}/\Lambda)\}\sin(2\pi(z+\Delta\Lambda_{ON}/2)/\Lambda)]$$

where $\Delta\Lambda_{ON}/\Lambda$ is the fraction of the period that the beam is on (i.e. the duty cycle).

For small values of $\Delta\Lambda_{ON}/\Lambda$ a near 100% grating contrast is obtained however the efficiency of the grating writing is reduced to $\sim\Delta\Lambda_{ON}/\Lambda$ because most of the UV beam is prevented from reaching the fibre.

The maximum grating strength is obtained for $\Delta\Lambda_{ON}/\Lambda=0.5$ however the ratio of dc to ac index change is worse. For $\Delta\Lambda_{ON}/\Lambda>0.5$ the grating begins to be reduced whilst the dc index change continues to build.

Experimentally, a good value for $\Delta\Lambda_{ON}/\Lambda$ has been found to be $\sim$0.3-0.4.

Thus, with embodiments of this technique, exposure of the grating lines or elements is repeated every grating period. Thus the footprint defined by the UV beam, which might for example for a 500μm diameter beam, ϕ_{beam}, consists of $\phi_{beam}/\Lambda(\sim 1000)$ lines, is significantly overlapped with the previously exposed lines. Significant averaging of the writing process given by $(\phi_{beam}/\Lambda)^{1/2}$ is therefore achieved, thus improving the effective accuracy and resolution of the system.

The computer in this embodiment actually generates the switching positions internally as "real" numbers (obviously subject to the limitation of the number of bits used), but then converts them for output to the controller into the same unit system as that output by the Zygo interferometer, namely multiples of a "Zygo unit" of 1.24nm. This internal conversion by the computer makes the comparison of the actual position and the required switching position much easier and therefore quicker for the controller. A random digitisation routine is employed in the computer 60 to avoid digitisation errors during the conversion from real numbers to Zygo units. This involves adding a random amount in the range of $\pm$0.5 Zygo units to the real number position data before that number is quantised into Zygo units. Thus an effective resolution can be obtained of:

$$1.24\text{nm}/(\phi_{beam}/\Lambda)^{1/2} \approx 0.03\text{nm}.$$

The technique offers the further advantage that the CW laser is extremely stable whereas pulsed lasers (as required in the technique proposed by Stubbe et al [7]) may suffer from pulse-to-pulse instability which, in the Stubbe et al technique,

is not averaged over multiple exposures. In addition the high peak powers of a pulsed laser may cause non-linear grating writing effects, which are avoided or alleviated by using longer and repeated exposures in the present technique.

A refinement of the above technique, for producing apodised gratings, will now be described with reference to Figure 3b.

Using the techniques described above, effectively controlling the grating writing process on a line-by-line basis allows accurate apodisation to be achieved.

Apodisation is achieved by effectively dithering the grating writing interferometer position in the fibre to wash out or attenuate the grating strength. However, if the overall duty cycle of the exposure is kept the same, and just the timing of each exposure dithered, the average index change along the grating is kept constant.

To completely wash out the grating subsequent on periods of the UV laser are shifted in phase (position) by $\pm\pi/2(\pm\Lambda/4)$. To achieve a reduced attenuation the amplitude or amount of dither is reduced. Figure 3b illustrates an applied dither of about $\pm\pi/3$ from the original (undithered) exposure times.

This technique of apodising is better with an exposure duty cycle of less than 50%, to allow a timing margin for 100% apodisation.

One example of the use of this technique is to generate a grating with a contrast increasing at one end of the grating according to a raised cosine envelope, and decreasing at the other end of the grating in accordance with a similar raised cosine envelope, and remaining substantially constant along the central section of the grating. This apodisation can be achieved particularly easily with the present technique, as the central section requires no phase shift between successive exposures, and the two raised cosine envelopes require a phase shift that varies linearly with longitudinal position of the fibre.

The required phase shifts can be calculated straightforwardly by the computer 60, under the control of a simple computer program relating required phase shift to linear position of the fibre (effectively communicated back to the computer 60 by the controller 70, whenever the controller 70 requests a next switching position data value).

Other apodisation schemes are also possible. Compared with previous

methods of dithering [6] this technique is not limited by the dynamics of a mechanical stage used for dithering, but instead simply adjusts the switching time of a non-mechanical modulator element 50. It can also achieve substantially instantaneous phase shifts.

Furthermore, arbitrary phase profiles and in particular a linear chirp can be built up by the computer 60 inducing phase shifts along the grating as it is fabricated. In a similar manner to the "Moving fibre/phase mask" technique [6] the maximum wavelength is inversely proportional to the beam diameter. However, with the present technique an improvement can be obtained (with respect to the technique of [6]) by incorporating a short, linearly chirped phase mask. Thus as the fibre is scanned the UV beam is also slowly scanned (by another PZT translation stage, not shown) across the phase mask. This scanning of the position of the UV beam in itself induces a small chirp, in accordance with the techniques described in reference [6], but more significantly the translated beam accesses writing lines of a different period allowing larger chirps to be built up. This has been tested using a 19mm diameter, ~20nm chirped phase mask (sourced from Lasiris) with its central period around 1070nm. This allows ~30nm chirped gratings centred around a central wavelength of 1550nm to be fabricated.

Figures 4a and 4b are schematic graphs showing the characterisation of a 20cm linearly chirped grating written at a fibre translation speed of 200μm/s with the basic technique described earlier, i.e. with a fixed mask. At this fibre translation speed, for a projected fringe pitch of 0.5μm the writing light beam is switched at a switching rate of 400Hz. In other words, the fibre advances by one projected fringe between exposures. (It is noted that the limitation on fibre translation speed in these prototype experiments is the calculation speed of the computer 60 used in the experiments, and that given a faster computer such as a Pentium or subsequent generation PC, much higher translation speeds of, say, 10mm per second or more would be possible).

In particular, therefore, Figure 4a is a graph of reflectivity against wavelength, and Figure 4b is a graph of time delay against wavelength. The wavelength (horizontal) axes of the two graphs have the same scale, which for clarity of the diagram is recited under Figure 4b only.

A ~4nm bandwidth and dispersion of ~500ps/nm are observed.

Such results have not been reported by any other method. Gratings up to 40cm and writing speeds up to 1mm/s have been demonstrated. Lengths in excess of 1m and writing speeds up to 10mm/s are feasible.

In the above description, the fibre has been translated with respect to the phase mask, and in the later description the UV beam is translated with respect to the phase mask. However, it will be clear that the important thing is *relative* motion, and so the choice of which component (if any) remains "fixed" and which is translated is relatively arbitrary. Having said this, however, the arrangement described above has been tested experimentally and has been found to be advantageously convenient to implement.

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CLAIMS

1. A method of fabricating an optical waveguide grating having a plurality of grating lines of refractive index variation, the method comprising the steps of:

(i) repeatedly exposing a spatially periodic writing light pattern onto a photosensitive optical waveguide; and

(ii) moving the writing light pattern and/or the waveguide between successive exposures of the writing light pattern, so that each of at least a majority of the grating lines is generated by at least two exposures to different respective regions of the writing light pattern.

2. A method according to claim 1, in which step (i) comprises moving the writing light pattern and/or the waveguide between exposures a by a distance, in a substantially longitudinal waveguide direction, substantially equal to an integral number of spatial periods of the writing light pattern.

3. A method according to claim 2, in which step (i) comprises moving the writing light pattern and/or the waveguide between exposures a by a distance, in a substantially longitudinal waveguide direction, substantially equal to one spatial period of the writing light pattern.

4. A method according to any one of claims 1 to 3, in which step (ii) comprises:

detecting the relative position of the writing light pattern and the waveguide;

comparing the detected relative position to predetermined switching positions related to the spatial period of the writing light pattern; and

controlling exposure of the writing light pattern in response to that comparison.

5. A method according to any one of the preceding claims, in which:

the writing light pattern is generated from one or more source light beams; and

exposure of the writing light pattern is controlled by directing the one or more

source light beams through one or more optical modulators.

6. A method according to claim 5, in which the writing light pattern is generated by directing the source light beam through a phase mask.

7. A method according to claim 5 or claim 6, in which the one or more source light beams are substantially continuously generated (CW) light beams.

8. A method according to any one of the preceding claims, in which step (i) comprises moving the writing light pattern and/or the waveguide at a substantially uniform relative velocity.

9. A method according to claim 8, in which step (i) comprises substantially periodically exposing the writing light beam onto the waveguide, the exposures having a substantially constant temporal duty cycle.

10. A method according to claim 9, in which step (i) comprises varying the time at which each exposure of the writing light beam is made to vary the spatial alignment along the waveguide of successive exposures, thereby varying the contrast of grating lines generated by those exposures.

11. A method according to any one of the preceding claims, comprising varying the spatial period of the writing light beam during fabrication of the grating.

12. A method according to claim 6 and claim 11, comprising directing the source light beam onto different regions of a chirped phase mask in order to vary the spatial period of the writing light beam during fabrication of the grating.

13. A method according to any one of the preceding claims, in which the waveguide is an optical fibre.

14. An optical waveguide grating fabricated by a method according to any one of

the preceding claims.

15. Apparatus for fabricating an optical fibre grating having a plurality of grating lines of refractive index variation, the apparatus comprising:

a writing light beam source for repeatedly exposing a spatially periodic writing light pattern onto a photosensitive optical waveguide; and

means for moving the writing light pattern and/or the waveguide between successive exposures of the writing light pattern, so that each of at least a majority of the grating lines is generated by at least two exposures to different respective regions of the writing light pattern.

16. A method of fabricating an optical fibre grating, the method being substantially as hereinbefore described with reference to the accompanying drawings.

17. Apparatus for fabricating an optical fibre grating, the apparatus being substantially as hereinbefore described with reference to the accompanying drawings.

18. An optical fibre grating fabricated using a method substantially as hereinbefore described with reference to the accompanying drawings.